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14. ABSTRACT

The ability to rapidly detect and process radio frequency (RF) signals is of extreme importance in the modern warfare environment. As the use of the electromagnetic spectrum continues to expand, the technical requirements necessary to maintain such a critical ability becomes very challenging; additional requirements such as miniaturization of the system, reduction in power consumption and the miniaturization of signatures places even more stringent requirements on an already pressing problem. To address these issues, we utilize advanced artificial materials - photonic crystals (PhCs) and meta-material - to construct a sensing head with minaturized antennas as RF receivers and embedded signal channelization for pre-processing. This sensor head can directly detect and process RF signals, significantly decreasing the response time on Naval platforms to potential threats. In this report, we present an overview of our work on theoretical design and experimental demonstration of miniaturized RF correlators and antennas based on meta-materials, as well as hybrid lattice PhCs and Schottky diodes for RF correlation and channelization.

15. SUBJECT TERMS

photonic crystals, meta-materials, RF sensing head, millimeter wave channelizer, millimeter wave correlator, miniaturized antennas

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Embedded RF Photonic Crystals as Routing and Processing
Devices in Naval Aperstructures

Final Report

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Abstract:

The ability to rapidly detect and process radio frequency (RF) signals is of extreme importance in the modern warfare environment. However, as the use of the electromagnetic spectrum continues to expand, the technical requirements necessary to maintain such a critical ability becomes very challenging. Moreover, additional requirements such as miniaturization of the system, reduction in power consumption, and perhaps most importantly the minimization of signatures places even more stringent requirements on an already pressing problem. To address these issues, we utilize advanced artificial materials, namely, photonic crystals (PhCs) and meta-materials, to construct a sensing head with miniaturized antennas as RF receivers and embedded signal channelization for pre-processing. This sensor head can directly detect and process RF signals, thereby significantly decreasing the response time on Naval platforms to potential threats. In addition, PhC based devices are electromagnetically transparent, which leads to a significant reduction in the scattering cross-section, or signature. Also, another significant advantage of the PhC is the ability of the device to scale with wavelength, which ultimately leads to ultra-compact systems. To this end, this report presents an overview of our work on experimentally demonstrated miniaturized antennas based on meta-materials, as well as, hybrid lattice PhCs and Schottky diodes for RF channelization. Based on these devices, we design a RF sensing head, which is composed of miniaturized antennas and correlators. To further decrease the size of the system, we also present our initial design and simulation results for a PhC slow wave delay line, which also functions as a waveguide to the channelized signals.

Technical Objectives

A critical capability in the modern warfare environment is to rapidly and accurately detect and process RF signals. However, the spectrum of such signals is rapidly increasing, which stresses the limits of current and next generation technology. In addition, there is also a pressing problem with limited space and location for such processors as well as accommodating the numerous radiating apertures that are needed to intercept the signals. In order to address these requirements, development and application

1

of cutting-edge technologies are needed to support surveillance sensors, communication links, and command and control systems. To support these capabilities, miniaturized antennas and sensors must be monolithically integrated to provide highly survivable, yet lightweight and reliable systems. However, present conventional electronic systems are not adequate to meet these standards mainly due to space and power restrictions.

A newly emerging class of artificially engineered materials, which is commonly known as Photonic Crystals (PhCs) and Metamaterials (Mms) offers significant promise in meeting these demanding needs. Using these advanced materials, we designed a sensor head which is based on the unique dispersion properties of photonic crystals to achieve waveguiding and correlation. The main advantage of this approach over conventional techniques is that these devices are, to a large extent, electromagnetically transparent and therefore have a significantly reduced scattering cross-section. Perhaps more importantly, photonic crystal components permit the realization of RF structures on a scale comparable to the RF wavelength, which enables the design of waveguides and antennas that are small and compact in size. In addition, to reduce the overall size of the sensor head it is also desirable to reduce the size of the detecting antennas. To address this problem, we used Mms, such as split-ring resonators (SRRs) to realize the reduced physical size antenna. These Mms exhibit electromagnetic behavior that is not prevalent in nature, and can be engineered to have functional electromagnetic response at a desired frequency range. Recently, one such engineered Mms with high positive magnetic permeability, otherwise artificial magnetic inductors is demonstrated that can significantly improve the performance of antenna.

Technical Approach

The modern warfare environment is fast becoming an electromagnetic jungle, of sorts, where the need for technologies that enable a direct interrogation of these signals from nearly every imaginable direction is imperative. Unfortunately, this is difficult to accomplish using current electronic based signal processing systems. To overcome this limitation, we propose to construct a front-end sensor head that can directly detect, filter and correlate signals using the integration of metamaterials and phtonic crystals. Accordingly, this sensor device is capable of immediate processing of large amounts of data with high efficiency. In addition, this direct data control allows processing of the desired signals without causing interference with other electronic equipments. This allows for a reduction in the size and weight of the whole system and, therefore, enhances the structural support and integrity of the various apertures in the superstructure.

First, unique to our approach will be the design, fabrication, and demonstration of an all-passive signal processing system in the millimeter wave (mmW) region of the electromagnetic spectrum by engineering the dispersion properties of the material. The underlying physics of this approach is based on photonic crystals, which are passive devices that consist of periodic arrays of localized structures, whose material constants, differ from that of the host material. Usually, a PhC can consist of a planar slab with an array of cylinders etched into a host material. More often, PhC devices are based on the region of interaction wherein the EM field is forbidden to exist within the lattice. A unique quality of the PhC is its ability in spatially and spectrally control of

electromagnetic waves, which allows wide bandwidth, high capability, small size, and low weight and cost warfare signal processing systems. In our prior research, we have demonstrated compact mmW waveguides based on engineering their dispersion properties. By this we mean that these waveguides do not contain any form of lateral confinement by way of physical structures. Lateral control is imposed on the propagating wave by virtue of engineering the band structure of the photonic crystal lattice, which significantly minimizes the cross-scattering section of the structure.

On the other hand, a major concern of constructing a miniature front-end sensing system is to reduce the size of the radar antennas. This is especially true in the field of radio communications, where reducing the size of an antenna leads to smaller and light-weight systems, thereby enhancing portability and minimizing electromagnetic interference with other electronic devices. Compact antenna design allows an embedded antenna on platforms of the ships, would thus minimize electromagnetic interference with other electronic devices. Thus, in accordance with such criteria, we propose to design a metamaterial based resonant antennas that are electrically responsive in that frequency range, yet physically small in comparison to conventional antennas in that range.

Antennas exploiting this feature have shown operate with a broader frequency bandwidth while simultaneously maintaining a reduced physical size. This extraordinary phenomenon offers the potential to overcome the restrictive efficiency-bandwidth product limitations that will efficiently utilize the space on military platforms. Most beneficially, the periodic Mms antenna structure offers an opportunity of integration with another artificial periodic structure, photonic crystals (PhCs), which dispersion properties can be engineered to provide the control, localization, guiding of signals. The integration of Mms antenna with PhCs offers an opportunity to construct an RF signal detecting and processing sensor head with miniaturize antennas as detecting devices. This sensor head can directly detect and process signals, thereby significantly increasing the response speed of the detection. Perhaps, the most significant advantage of this sensor head is its wavelength scale size, which allows compact systems with dense integration and high-speed operation. This highly sensitive and compact RF detecting and processing sensor head with the integration of multiple functions into a superstructure can be achieved by harnessing the atypical nature of the Mms by increasing the efficiency, bandwidth, of the antenna arrays while reducing the overall size, weight and cost of the entire system.

The challenge in realizing this goal arises from the fact that as an antenna is reduced in size, its wavelength dependence posses a strict limitation on the dimension of the antenna, thus, making it harder to reduce in size. For this reason, alternative designs based on synthetic reactive components must be used, our approach to which is described below. It has been shown that resonant antennas can be miniaturized using a new class of Mms, artificial magneto dielectrics, while maintaining and improving the bandwidth of the antenna. The fundamental reason for this is based on the fact that the resonant frequency of an antenna is inversely proportional to its inductance (L) and capacitance (C), such that an increase in either will decrease the resonant frequency. As a result, in order to increase the resonant frequency back to its original value, the physical dimension of the antenna must be reduced, thus resulting in an antenna with a smaller physical

dimension. Furthermore, an inductive element is preferred over a capacitive one, as the former leads to an increased bandwidth. However, typical inductive elements are based on ferromagnetic materials, and, unfortunately such materials have a very weak electromagnetic response in the GHz frequency range. To overcome this limitation, the use of artificial magnetic materials have been called for in which SRRs have been the front-runner as they exhibit paramagnetic behavior well into the high GHz range.

Progress Statement Summary

In this project, we designed, fabricated and characterized a PhC and Mm based analog mmW sensor head for direct signal detection and processing. This signal processing method offers ultrawide bandwidth, immunity to electromagnetic interference, flexibility and compactness. Accordingly, this sensor device is capable of immediate processing of large amounts of data with high efficiency. To further miniaturize the system, we consider using a rectangular resonant loop antenna for receiving signals. The rectangular resonant loop antenna is omnidirectional in nature, which has wide appeal in the communication community, which, when miniaturized, can have important military applications in wireless communications, sensing and time domain spectroscopy. However, it has dimensions on the order of a quarter-wavelength on each side. To deal with this, we introduced reactive and inductive elements between the antenna and the ground plane. The simulation and experimental results show this structure can achieve 31% reduction in size while providing the same resonant frequency in comparison with conventional patch antenna.

For processing the signal, we utilize the special dispersion properties of the PhC to design a hybrid lattice structure that has the ability of channelizing, taping, delay and mixing signals. We experimentally demonstrated the channelizing and taping capability of the structure. The key advantage of the device is its ability of real time processing of signals and compactness with the waveguiding, delay and taping of signals functionally integrated in a PhC waveguide. To mix the signal for the correlation, we introduce Schottky diode mixers into the PhC waveguide structure. We experimentally tested the I-V curve of the fabricated Schottky diode. In the future, we will continue our work on integrating the mixers, antennas and the PhC taping structure to obtain a compact mmW sensor head for direct signal processing propose.

Progress to Date

1. Correlator design

The main functionality of a correlator is to compare two incoming signals. At the appropriate sampling time, a maximum autocorrelation peak will be produced if the two input signals are exactly matching each other. This function has historically been used in conjunction with special coding techniques to pick a desired signal out of noise, an essential requirement for RADAR and code-division multiple-access systems.

In this report, we will present a corrrelator for realization of an all-passive signal processing system in the millimeter wave (mmW) region of the electromagnetic spectrum by engineering the dispersion properties of the material. The underlying physics of this approach is based on photonic crystals, which are passive devices that consist of periodic arrays of localized structures. In our approach, the lateral control is imposed on the propagating wave by virtue of engineering the band structure of the photonic crystal lattice, which significantly minimizes the cross-scattering section of the structure. If we introduce a triangular lattice with point defects in the form of cavities adjacent to the dispersion engineered waveguide, signals with a frequency coincident with the resonance frequency of the respective cavity will drop from the waveguide to the cavity. Accordingly, this configuration can be used to design compact correlators that can be embedded in the superstructure of ships.
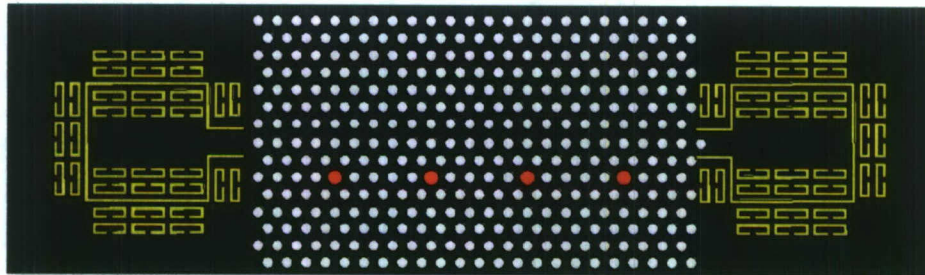

Figure 1. Photonic crystal sensor head system.

The detailed configuration of the correlator is shown in Fig. 1. Two separate signals are captured by Mm antennas, which are then fed into a PhC waveguide propagating toward each other. Utilizing the combination of the dispersion and bandgap properties of photonic crystals, we can control the tapping of the counter propagating signals as they interact with each cavity. The beauty of the PhC waveguide is that the group velocity of the wave can be designed to be very slow. Therefore, it offers a time delay between each cavity. As such, the waveguide not only serves as a guiding structure, it also provides the sufficient relative time delay required for correlation of the two signals. Once the two signals are taped sequentially in time by the cavities, a Schottky diode mixer, which is

located inside the cavities, serves to multiple the tapped signals with the resulting product being routed through a drop channels and subsequently to a detector to be integrated.
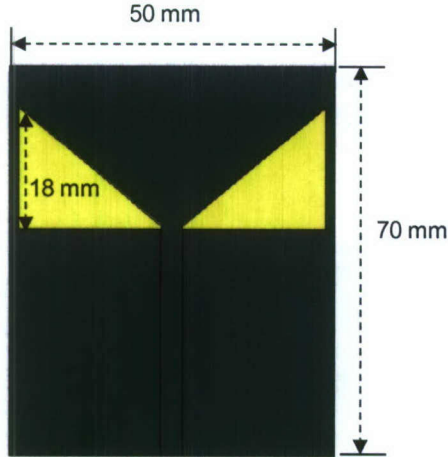
2. Wide Band Bowtie Antenna

Figure 2. Bowtie antenna design for the correlator

The first step to realize this an Mm correlator design is to construct ultra-wideband (UWB) antennas to capture the signals. UWB technology is currently spreading in different areas, such as radar or communications, due to its many advantages as well as its low-spectral-density radiation power. However, in UWB communications, the conception of the antenna presents specific difficulties which result from the compromise between bandwidth, size, radiation efficiency, and low cost. In particular, in order to cover the wide detecting range, the chosen structure needs to maintain good impedance matching for a wide band, and keep its omnidirectional radiation characteristic on the entire bandwidth. Finally, to facilitate integrated communication systems, a 2D printed antenna matched to 50Ω will be preferable.

Relatively large antennas, for example, log-periodic or horn antennas, as well as resistively loaded antennas which have low efficiency, are thus less appropriate. On the other hand, several other kinds of radiating elements, such as spiral, or bow-tie, antennas, which have very good impedance stability over a very large frequency band, are suitable and widely used for these applications. Among them, bowtie antennas have been of much interest in developing high data rate systems due to their advantages, such as low profile, simple structure, and wide bandwidth.
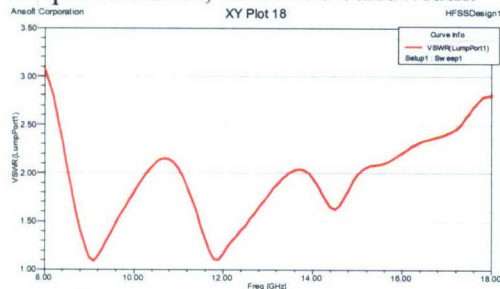

Figure 3. VSWR of the bowtie antenna

Accordingly, we designed and optimized the bandwidth and radiation pattern of a bowtie antenna using Ansoft HFSS software. The geometry of the CPW fed antenna is shown in Fig. 2. The width, length of the antenna is about 18 mm and 45 mm respectively. The antenna bandwidth covers the frequencies from 8.3 to 14.5 GHz for the voltage standing-wave ratio (VSWR) < 2, as shown in Fig. 3.

3. Antenna Miniaturization using Metamaterials

The second step is to miniaturize the UWB antenna. Since there is a growing need for compact communication systems, the need for physically small devices is imperative. From a Naval perspective, ship superstructure design integrates several critical mission performance requirements, which include structural integrity, antenna performance, and signature control. Future Navy ship designs seek an integrated solution to this topside design challenge. A current approach that is being pursued requires combining the functionality of radiating apertures monolithically into the structure, so named "aperstructure." In this approach the goal is to fully integrate antenna apertures into a composite topside structure while maintaining required signature control. A properly engineered aperstructure would proactively address antennas, signature, electromagnetic interference, and mechanical considerations in an integrated fashion. This can only be accomplished with the development of suitable antennas, structural absorbing materials, and structural isolation materials.

In our approach, a major concern of constructing a miniature front-end sensing system is to reduce the size of the radar antennas. The challenge in realizing this goal arises from the fact that as an antenna is reduced in size, its wavelength dependence posses a strict limitation on the dimension of the antenna, thus, making it harder to reduce in size. For this reason, alternative designs based on synthetic reactive components must be used. In our previous effort, it had been shown that resonant antennas can be miniaturized using a new class of Mms, artificial magneto dielectrics, while maintaining the bandwidth of the antenna. The fundamental reason for this is based on the fact that the resonant frequency of an antenna is inversely proportional to its inductance (L) and capacitance (C), such that an increase in either will decrease the resonant frequency. As a result, in order to increase the resonant frequency back to its original value, the physical dimension of the antenna must be reduced, thus resulting in an antenna with a smaller physical dimension. Furthermore, an inductive element is preferred over a capacitive one, as the former leads to an increased bandwidth.

However, typical inductive elements are based on ferromagnetic materials, and, unfortunately such materials have a very weak electromagnetic response in the GHz frequency range. To overcome this limitation, the use of artificial magnetic materials have been called for, in which SRRs have been the front-runner as they exhibit paramagnetic behavior well into the high GHz range. To study how to reduce the physical size of antennas, we considered loading antennas with SRRs and investigated the impact on some of the main antenna parameters, such gain, impedance, front to back, resonance and effective electrical length.

We proposed a monolithic design of the SRRs, where the antenna and the split rings are on the same plane, as shown in Fig. 4 (a). The motivation for this configuration stems from the fact that the magnetic field is rotationally symmetric around the current carrying path of the loop. We designed an antenna having the dimension of approximately one quarter-wavelength on each side, such that the total perimeter was approximately one wavelength. The resonant frequency of the antenna was 2.6 GHz. Rings of dimension

9mm x 3mm with the resonant frequency of around 2.8 GHz were placed 1mm away from the antenna and from each other on the same plane around the loop. The SRRs had a higher resonant frequency than the antenna, enabling it to exploit the paramagnetic region of the rings. With the introduction of the first layer of SRRs, the resonant frequency of the antenna went down to 1.7 GHz from 2.58 GHz and with the addition of extra layers, the resonant frequency went down to 1.6 GHz. Hence, with the in-plane configuration the miniaturization of the antenna was possible up to 37.9%! Lastly, we should note that the radiation pattern of the loop was omni directional, as was expected.

(a)   (b)   (c)
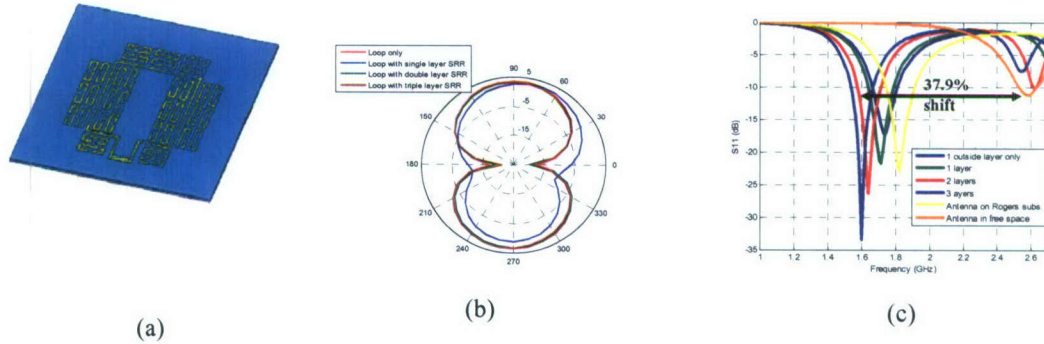
Figure 4. (a). In-plane SRR configuration, (b). Radiation pattern of the loop antenna with the in-plane SRRs. (c). Shift of resonant frequency of the loop antenna with the in-plane SRRs.

With the promising results obtained from simulation, we proceeded to design a 1.85 GHz dual loop antenna. SRR slabs, each containing 9mm x 3mm rings arranged in a 5 x 2 array fashion, were sandwiched between the loop antennas, Shown in Fig. 5. The antenna consisted of a driven element and a slightly shorter director element. The frequency decrease ranged from approximately 1.85 GHz to 1.65 GHz. There was an increase in bandwidth for the SRR loaded dual loop antenna. Thus, the experimental results justified the assumptions made through the simulation concerning a corresponding shift in the resonant frequency of the antenna.
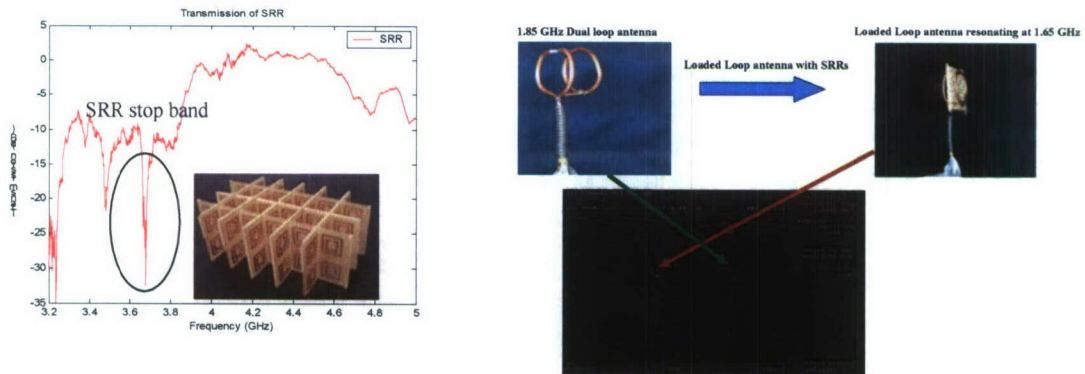

Figure 5. Experimental testing results of an SRR antenna.

4. Broad Band Antenna Miniaturization

For the correlator application, broadband antennas, such as bow-tie antennas are more appropriate. Therefore, we explored metamterials for the miniaturization of bowtie antennas. The antenna can be designed to resonate around 2.5 GHz and can have a bandwidth of 43%, shown in Fig. 6. Efforts will also include characterizing these antennas in terms of their gain and radiation efficiency. Following the design of the antenna, we would be investigating different Mms that can effectively reduce the physical dimension of the antenna without compromising the bandwidth. One particular approach would be to investigate the effect of SRRs surrounding the antennas as shown in Fig. 6 for miniaturization purposes. The primary objective of the SRRs is to follow the current flow on the antenna so that the SRRs can be induced by the magnetic flux, which is rotationally symmetric. In that regard, the antenna and the SRRs could be on the same plane, thus avoiding any unnecessary increase in the net volume of the overall structure. Moreover, an added advantage of this configuration is the ease of the fabrication procedure. The general approach will be similar to our previous efforts in size reduction of narrow band antennas such as the patch and loop antennas, where we tried to observe a shift in the resonant frequency of the antenna after the introduction of the Mm.
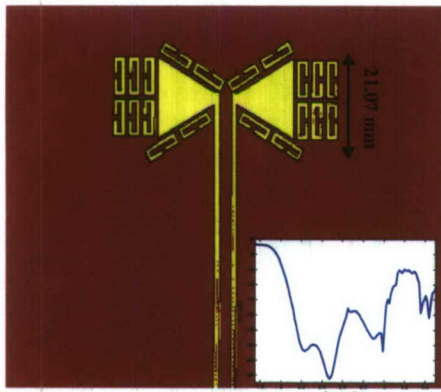

Figure 6. Bow-tie antenna with SRRs

The percentage shift in the resonant frequency determines the percentage of the actual physical size reduction that can be achieved. However, in this case, the relatively larger bandwidth of the bow-tie antenna can pose a problem as the SRRs, on the contrary, tend to have narrower bandwidth. We plan to mitigate such problems by combining SRRs of different dimensions whose resonant frequencies will overlap to provide a collectively higher bandwidth. Furthermore, we will investigate the radiation efficiency, gain and radiation pattern of the miniaturized version of the antenna.

2. Photonic Crystal Signal Channeling and Taping Structure

Our next step towards the realization of the Mm correlator is the design, fabrication and characterization of the photonic crystal signal channeling and taping structure. Among the properties of photonic crystals, the unique dispersion and the bandgap are two representative characteristics that allow for designing devices by engineering the dispersion property or introducing point- and line-defects into PhCs. The dispersion property offers the electromagnetically transparent property and thereby significantly reduced the scattering cross-sections of devices. The bandgap property provides various functional devices, including channelizers, correlators, and filters. Generally, these devices are based on a single lattice or single property, such as line-defect waveguides based on a triangular lattice, and self-collimation based on a rectangular lattice. However, for the goal of eventually incorporating of different photonic crystal based devices into

subsystems or systems, hybrid of different lattices is an essential task. In particular, it enables one to design more complex devices by combining different properties of the PhCs. Therefore, we proposed and demonstrated devices based on the combination of these two approaches that allow for both low scattering cross-section and functional devices.

The proposed hybrid lattice structure is based on the hybrid of the rectangular and triangular lattices of air holes on a slab, as shown in Fig. 7. The second pass band of the rectangular lattice is designed to be in the bandgap of the triangular lattice, as shown in Fig. 8.
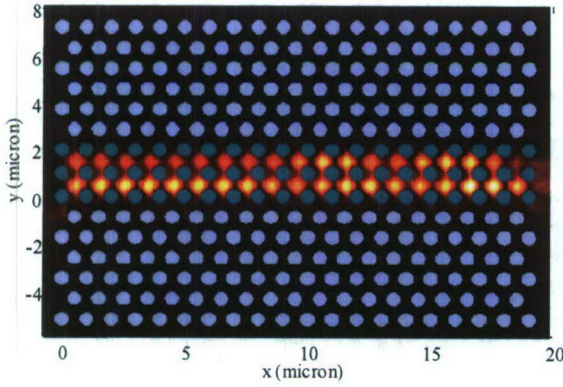

Figure 7. Hybrid lattice structure of photonic crystal

The rectangular lattice is designed to serve as the self-collimation waveguide to obtain low-loss propagation. To understand the self-collimation, we first introduce the unique dispersion property of the photonic crystal. The dispersion surfaces of photonic crystals gives one the ability to predict the direction of light propagating in a PhC by studying the shape of its equi-frequency surfaces (EFCs). Unlike ordinary materials which have ellipsoidal-shaped EFCs. PhCs can exhibit a wide variety of EFC shapes, which can be modified by manipulating the parameters of the PhC lattice, such as the lattice type, pitch, and fill-factor. If the EFC is a square-like shape, the directions of the group velocity are mostly limited to the two directions perpendicular to the square edges. If light is launched toward one edge of the EFC in a wide range of angles, it is only able to propagate in a narrow range of angles in the material. In this situation, light propagation in the PhC is self-collimated, which results in low scattering cross-section in the waveguide.
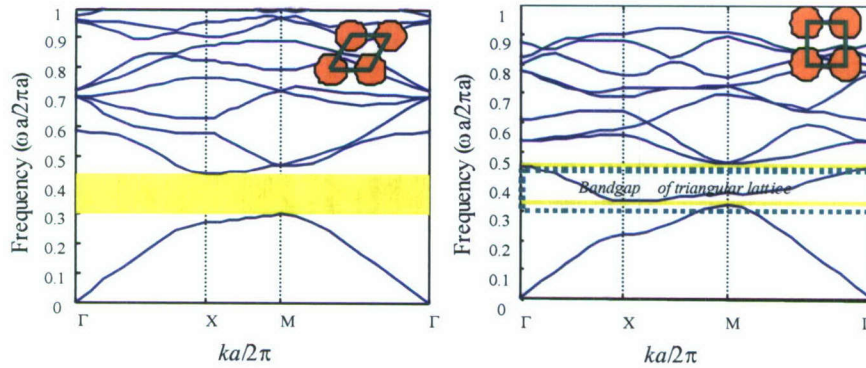

Figure 8. Dispersion diagram of rectangular and triangular lattice structure

The propagation loss can be further minimized by the triangular lattice, which serves as an efficient boundary to confine light in the in-plane. The triangular lattice can also function as a base to introduce point-defects into it to form cavities serving as tapping structures of the correlator.

To experimentally validate the design, the hybrid lattice PhC structure was fabricated on a 2.38 mm thick dielectric slab with a permittivity of 12.5 using a computer numerical controlled (CNC) machine, as shown in Fig. 9. The fabricated structure was characterized by using an Agilent 85106D network analyzer based system, shown in Fig. 9. A TE-polarized mmW with the wavelength swept from 10 GHz to 14 GHz was fed into the device. A monopole detector was used to map the surface of the device to detect the surface scattered field. The detected signals were feedback to the network analyzer and processed for the resulting of the surface scattered field pattern of the device. The structure is also simulated using the 2-FDTD as shown in Fig. 9. In both cases, the dropping of the particular wavelength of the wave are demonstrated.
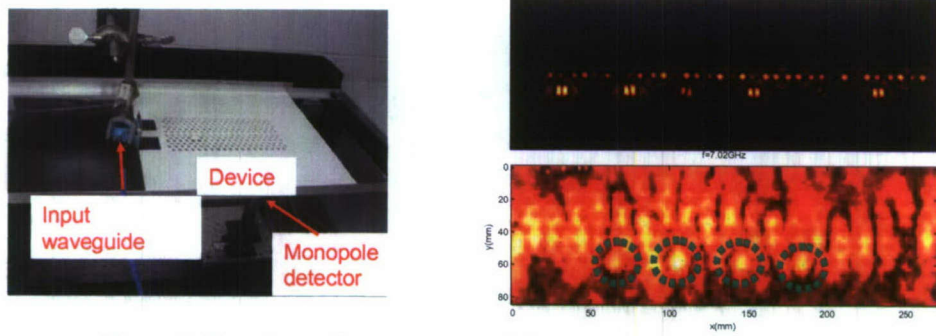

Figure 9. Experimental measurement of the taping structure of the correlator

3. Slow Light Effect as Delay Line

The photonic crystal hybrid lattice structure provides the tapping mechanism that split the signal into several branches. However, in order to realize the correlation function, it needs successive delays among these tapped signals to form a tapped-delay-line structure for the mixing of the signals. Each successive delay line adds one additional bit of delay to the incoming signal before the combiner, where the powers of the signals are added to yield the correlation output function. The tiny distances required to achieve delays in the structure present a serious challenge for the correlation.

To deal with this issue, we utilized the slow-light effect of the PhC waveguide to provide the sufficient time delay between the signals. One of the most fascinating properties of dispersion engineering in photonic crystals is integrated slow light waveguides where light can be slowed down to a fraction of the light speed c in vacuum. Slow light propagation in photonic crystal waveguides (PhCWs) has been widely studied and group velocities below c/300 were experimentally demonstrated. Slow light opens the way to practical applications, including compact wavelength converters, optical filters, modulators and delay lines.

11

The mechanism of slow-light effect can be explained as such. When light is incident into a crystal, it is coherently backscattered at each unit cell of the crystal, so the crystal acts as a one-dimensional grating. If the forward propagating and the backscattered light agree in phase and amplitude, a standing wave results, which can also be understood as a slow mode with zero group velocity. If the forward and backward traveling components begin to move out of phase but still interact, resulting in a slowly moving interference pattern. Small group velocity is crucial in a variety of applications, ranging from optical delay components and low threshold lasers, to the study of nonlinear optics phenomena. Although photonic crystals can be employed to achieve slow group velocities at their band edges, this is limited to a very narrow range of wave vectors in one particular direction. Recently, coupled resonator optical waveguides (CROWs) in photonic crystals were proposed for reducing the group velocity in a wide range of wave vectors, but still only for propagation in a narrow region along the waveguide axis.

We describe the design of a two-dimensional (2D) photonic crystal resonator that exhibits flat bands (reduced group velocity) over the entire range of wave vectors and in all crystal directions. This decreases the sensitivity of coupling and minimizes the distortion of the signal propagating through the structure. Therefore, it is an ideal candidate for constructing delay components. At the same time, this photonic crystal resonator structure also serves as a waveguide for signal propagation.
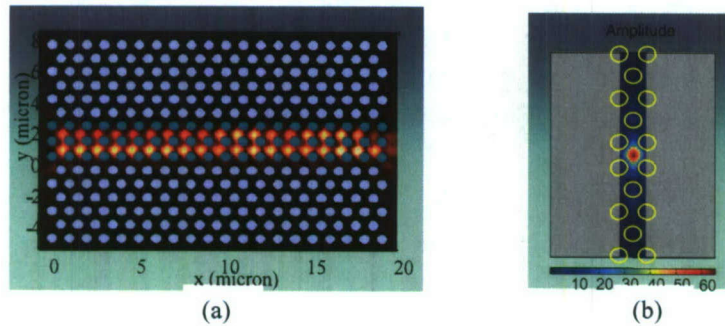

(a)   (b)

Figure 10. 2-D FDTD (a) and 2D-PWM (b) steady state simulation results of the photonic crystal waveguide

Figure 10(a) shows the 2D-FDTD simulation of the wave propagating in the hybrid lattice self-collimated. The mode profile of the wave is a cavity-like mode indicating a slow group velocity, as shown in Fig. 10(b). From the dispersion diagram, we can find that the waveguide mode is a flat curve within the bandgap, which means very low group velocity, as shown in Fig. 11(a). Figure 11(b) shows that the wave propagates in the waveguide at the speed between 0.03c and 0, where c is the speed of light.
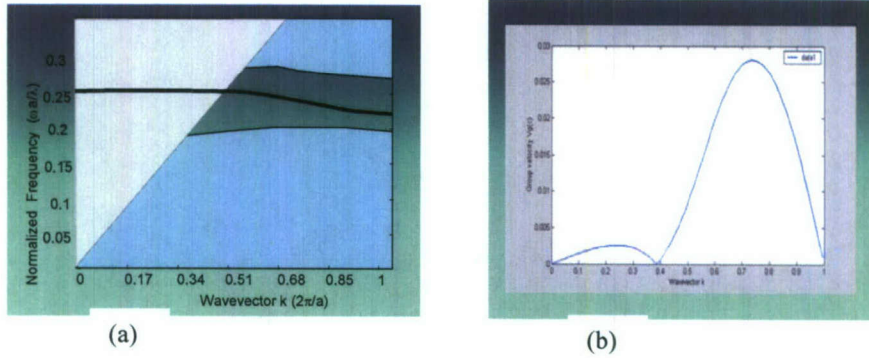
Figure 11. 2D-PWM simulation of dispersion diagram and group velocity verse wave vector

3. Schottky Diode Mixers

After the signal and its delayed counterpart dropped to the cavities, a device, which functions to multiple these signals are needed to obtain the correlation, as shown in equation (1), where τ is the time delay.

$$R(t) = \int_0^\tau f(\tau)f(t+\tau)d\tau \tag{1}$$

A mixer, which is illustrated in Figure 12, is fundamentally a multiplier. Although, in theory, any nonlinear or rectifying device can be used as a mixer, only a few devices satisfy the practical requirements of mixer operation. Any device used as a mixer must have a strong nonlinearity, low noise, low distortion and adequate frequency response. The nonlinear device most often employed for mixing is the Schottky barrier diode, a diode consisting of a rectifying metal-to-semiconductor junction.
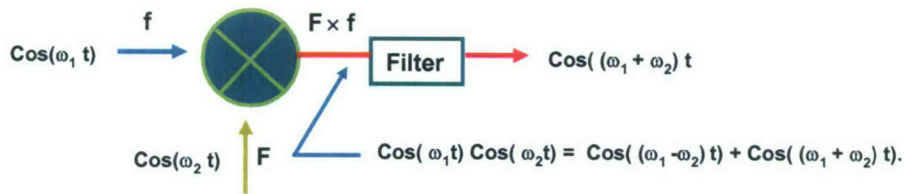

Figure 12. Illustration of the mixer

The Schottky-barrier diode is formed by a metal contact to a semiconductor, instead of the more common junction between p- and n-type semiconductors. Schottky diodes differ from pn-junction devices in that rectification occurs because of differences in work function between the metal contact and the semiconductor, rather a nonuniform doping profile. Conduction is not controlled by minority carrier recombination in the semiconductor, but by the unequal work functions. The Schottky diode is, therefore, a majority carrier device whose switching speed is not limited by minority carrier effects. These give Schottky diode the advantages of fast switching speed and low forward drop. Together with their well-known nonlinear current/voltage (I-V) characteristics, Schottky diodes have been used as mixers in vast variety of applications for many years. Amongst

13

others, they work as low-noise mixers in heterodyne receivers at frequencies up to 5 THz. In addition, due to this excellent high frequency performance, they have been widely used in power detection and microwave network circuit.

In our approach, to achieve the goal of mixing the tapped signals in the cavities, we designed to incorporate Schottky diode mixers into the cavities. The Schottky diode mixer will mix the signals with the resulting production channel out to a detector for subsequent integration. Schottky diodes are often fabricated by depositing metals on n-type or p-type semiconductor materials such as GaAs and SiC. When these two materials are brought into contact with each other, the difference in potential gives rise to a barrier height that the electrons have to overcome for current to flow. The metal on the low-doped semiconductor is the anode and the semiconductor material, which contacted through an Ohmic contact, is the cathode. The nonlinear resistance of these point-contact diodes is used to realize the mixing function, as shown in equation (2).

$$I = I_s \exp[\frac{V - IR_s}{nV_t}]\left\{1 - \exp[\frac{V - IR_s}{V_t}]\right\}$$ (2)

Where V is the bias voltage, I_s is the saturation current, R_s is the series resistance, V_t is the thermal voltage equal to KT/q, and n is the SBD ideality factor.
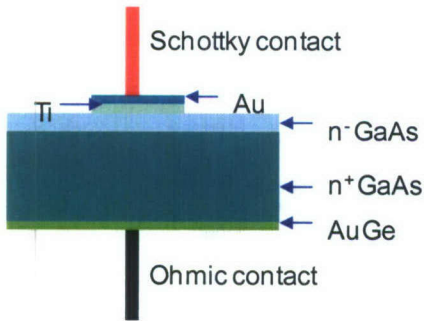

Figure 13. GaAs Schottky diode structure

Accordingly, we fabricated the Schottky diode structure on a GaAs wafer for signal mixing purpose. Molecular beam epitaxy (MBE) has been used to grow a thin n-layer of GaAs on top of the n+ doped substrate. The Schottky diode structure is defined by electron-beam lithography, as shown in Fig. 13. Layers of Au and Ti were evaporated on top of the structure using electron beam evaporation technique. A lift-off process is followed to reveal the Schottky contact. Metal evaporation was performed on the back of the wafer to result in an Ohmic contact for the Schottky diode. Figure 14 shows the tested I-V curve of the Schottky diode. With the proper design, this Schottky diode can be used as the mixer for the purpose of the multiplication of the two signals in the cavity.

Figure 14. Fabricated Schottky diode mixers for mixing the RF signals.

Publications Resulting from this Program

1. C.Lin, Z. Lu and D. W. Prather, "Demonstration of compact microwave photonic crystal channelizers and displacement tunable filters," IEEE 2006 Wireless and Microwave Technology Conference, Dec. 4. 2006, Clearwater, FL USA

2. I. Mirza, S. Shi, J. Mait, C. Fazi, D. Prather, "Miniaturized Antennas for Compact Soldier Combat Systems," Proc. 25th Army Science Conference, Orlando, FL, 2006.

3. C. Fazi, S. Shi, I. Mirza, D. Prather, "Split ring resonator slab modeling for a metamaterial loaded loop antenna," Applied Computational Electromagnetics Society Conference, Verona, Italy. 2007.

4. C. Lin, Dennis W. Prather, "A Novel Sensor Chip Based on Photonic Crystal Correlators," IEEE AP-S Conference, Honolulu, Hawaii, USA. 2007.

5. Iftekhar O. Mirza, S. Shi, Chris Fazi, Joseph N. Mait and Dennis W. Prather, "A Study of Loop Antenna Miniaturization Using Split Ring Resonators," IEEE AP-S Conference, Honolulu, Hawaii, USA. 2007.

6. C. Lin, I. O. Mirza, S. Shi and D. W. Prather , "A Correlator Sensor Chip Based on the Integration of Meta-materials and Photonic Crystals," IEEE MTT Symposium, Atlanta, Georgia, USA 2008